Test of the polarization-analyzing power equality in two ($\vec{p}$,d) reactions and their inverses

B. L. Burks, R. E. Anderson, T. B. Clegg, H. Paetz gen. Schieck,*
E. J. Ludwig, R. L. Varner, and J. F. Wilkerson
Deparment of Physics and Astronomy, University of North Carolina, Chapel Hill, North Carolina 27514
and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27706
(Received 5 October 1981)

Angular distributions of vector analyzing power, A_y, were measured for the ^{11}B($\vec{p}$,d)^{10}B and ^{13}C($\vec{p}$,d)^{12}C reactions. These analyzing powers were measured for each reaction at seven energies, 100 keV apart, which spanned the same excitation-energy range in the compound nuclei, ^{12}C and ^{14}N, as existing measurements of the outgoing proton polarization, P_y, in the inverse reactions, ^{10}B(d,$\vec{p}$)^{11}B and ^{12}C(d,$\vec{p}$)^{13}C. We find general agreement between P_y and A_y except in a region where the P_y measurements are known to be difficult to make. We are not yet convinced that this difference constitutes evidence for a violation of time-reversal invariance.

[NUCLEAR REACTIONS ^{11}B($\vec{p}$,d)^{10}B measured $A_y(\theta,E)$ for $E=11.34$ to 11.94 MeV. ^{13}C($\vec{p}$,d)^{12}C measured $A_y(\theta,E)$ for $E=13.79$ to 14.39 MeV.]

I. INTRODUCTION

Recently, Conzett *et al.*[1] claimed to have found evidence for a violation of time-reversal invariance. Their claim is based on observed differences between the outgoing particle polarization, P_y, in the ^{7}Li(^{3}He,$\vec{p}$)^{9}Be reaction and the analyzing power, A_y, in the time-reversed reaction, ^{9}Be($\vec{p}$,^{3}He)^{7}Li. The reported differences were much larger than the statistical errors and too large to be attributed to the weak interaction. Smaller, but still significant, differences were observed in a second experiment when P_y for ^{9}Be(^{3}He, $\vec{p}$)^{11}B was compared with A_y for ^{11}B($\vec{p}$,^{3}He)^{9}Be. These data, if correct, would represent the first case where the strong interaction was seen to violate one of the fundamental quantum mechanical symmetries. In the past two decades a number of violations of fundamental quantum mechanical symmetries have been observed which have been attributed to weak interaction processes.[2–5] We have examined the polarization-analyzing power equality independently of the results of Conzett *et al.*[1] in a similar mass and excitation energy region by comparing previous P_y data for a single neutron transfer reaction to our new measurements of A_y in the time-reversed reaction at the same excitation energy in the compound nucleus.

II. EXPERIMENTAL METHOD AND RESULTS

We obtained from the literature two sets of polarization data each with relatively small error bars compared to typical polarization measurements, and reasonably large values of P_y over a large angular range. One set[6] is for ^{12}C(d,$\vec{p}$)^{13}C at $E_d=11.35$ MeV, and the other[7] is for ^{10}B(d,$\vec{p}$)^{11}B at $E_d=2.05$ MeV, where E_d is the bombarding energy of the incident deuteron beam before entering the target material. Polarized proton beams of the appropriate energy for the time-reversed reactions were obtained from the Triangle Universities Nuclear Laboratory (TUNL) tandem Van de Graaff accelerator and analyzing powers, A_y, were measured for ^{13}C ($\vec{p}$,d)^{12}C and ^{11}B($\vec{p}$,d)^{10}B.

Each set of measurements utilized four identical detector telescopes mounted in a 60-cm diameter scattering chamber. Two detectors were mounted to the right of the beam and two at identical angles to the left. In order to utilize particle identification, the telescopes consisted of ΔE-E (energy loss-

 ©1982 The American Physical Society

energy) detector pairs for the ^{13}C target and a ΔE-E-E_{veto} triple-detector combination for the ^{11}B target. Particle separation was routinely possible for the ^{13}C($\vec{p}$,d)^{12}C analyzing power measurements, as witnessed by the typical spectra shown in Fig. 1. The deuteron spectra for the ^{12}C ground and first excited state have no significant background.

For the ^{11}B($\vec{p}$,d)^{10}B reaction the low energy of the deuteron reaction products and the presence of proton and alpha-particle groups both of low energy required care while measuring A_y. Very thin detectors, 5—10 μm thick, were used as ΔE detectors, while 100 μm thick E detectors were employed. All of the deuteron reaction products were stopped in these E detectors; however, many of the scattered protons were energetic enough to penetrate beyond the E detectors to veto counters placed immediately behind the normal ΔE-E detector pair. The signals from these veto detectors were then used in anticoincidence to prevent the storage or misidentification of the signals from protons which were not stopped by the initial ΔE-E detector pair. The ΔE-E detectors then provided particle identification of the low-energy reaction products. Alpha particles were easily separated from the lighter particles; however, from Fig. 2 one sees that the deuteron

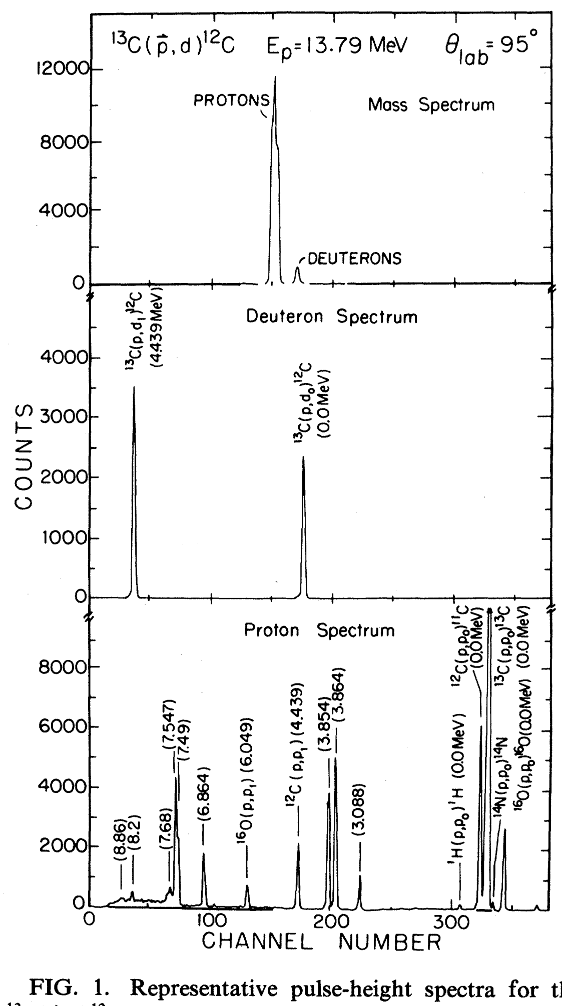

FIG. 1. Representative pulse-height spectra for the ^{13}C($\vec{p}$,d)^{12}C reaction at 13.79 MeV and lab angle 95°. The top spectrum is the result of a mass identification computer program which plots yield versus mass. The reaction products are clearly separated into a proton group and a deuteron group. The middle spectrum plots yield versus energy for events which are stored in the deuteron peak of the mass spectrum. The bottom spectrum plots yield versus energy for events which are stored in the proton peak of the mass spectrum.

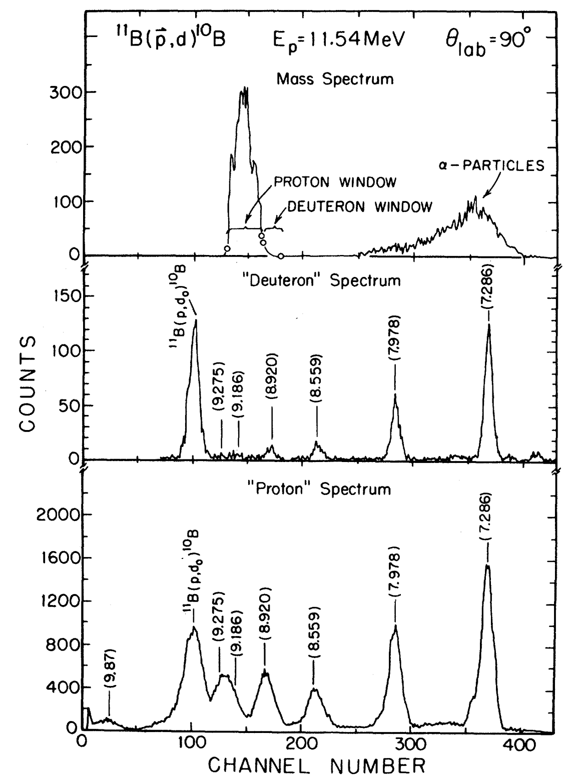

FIG. 2. Representative pulse height spectra for the ^{11}B($\vec{p}$,d)^{10}B reaction at 11.54 MeV and lab angle 90°. The top spectrum is the result of a mass identification computer program which plots yield versus mass. The reaction products are separated into two groups, protons and alpha particles. The shoulder on the right side of the proton group is the yield from deuterons. The middle spectrum plots yield versus energy for events which are stored in the deuteron window of the mass spectrum. The bottom spectrum plots yield versus energy for events which are stored in the proton window of the mass spectrum. Since the proton and deuteron counts are not well separated in the mass spectrum both protons and deuterons appear in the lower two spectra.

contribution to the mass spectrum is a distinct shoulder on the peak formed by low-energy inelastically scattered protons. For this reason it was necessary to set particle windows such that the "proton" gate stored low-energy proton peaks as well as some deuterons, while the "deuteron" gate stored the remainder of the deuteron counts as well as some proton counts. The mass windows were regularly checked at each new scattering angle to minimize contamination of the deuteron peak in the deuteron spectrum by protons. Typical spectra for both mass windows are shown in Fig. 2.

Deuteron counts were extracted from all spectra by peak fitting using the code MUFFIT.[8] The deuteron peak of interest directly overlapped an inelastically scattered proton peak at only a few angles. To insure that the analyzing powers measured for each angle would not contain some bias because of unknown levels in ^{10}B, proton background, or by the fact that all of the deuteron counts were not stored in one spectrum, etc., asymmetries were calculated for the deuteron peak seen in both the proton and the deuteron spectrum. Where the deuteron peak was not contaminated by a proton peak, the two spectra gave analyzing powers equal within the statistical uncertainties. Thus the results were simply averaged to determine the asymmetry reported in this work. For the few angles where the deuteron peak overlapped an inelastic proton peak to such an extent that reliable peak fitting was not possible, no asymmetry was extracted from the proton spectrum.

Measurements were made both with incident proton spin up and down for each angle, with the mass windows held constant during this sequence. The analyzing power was obtained from the experimental quantities by the method of Ref. 9. This method causes instrumental asymmetries to cancel in first order. The incident beam polarization was measured simultaneously with the A_y measurement for each angle using a ^{4}He($\vec{p}$,p)^{4}He polarization monitor.[10] The ^{13}C target used for all measurements was 20 keV thick; the ^{11}B target was 6 keV thick. Both targets were self-supporting foils. The magnet constant for the analyzing magnet which determined the proton beam energy for the analyzing power measurements reported in this work has been recently determined in an experiment in which two resonances whose energies are well known from the literature were studied. The ^{12}C(p,p)^{12}C resonance at 14.231 MeV and the ^{28}Si(p,p)^{28}Si resonance at 5.838 MeV were observed under various image and object slit conditions to determine the absolute energy of the proton beam and reproducibility of the beam energy under various beam steering conditions. All beam energies for the present measurements are accurate to within ± 15 keV.

Angular distributions of A_y in the ^{13}C($\vec{p}$,d)^{12}C reaction were obtained at seven energies between $E_p = 13.79$ and 14.39 MeV in 100 keV steps. The target in the ^{12}C(d,$\vec{p}$)^{13}C polarization measurement was about 500 keV thick; therefore, we measured A_y for proton energies of about ± 300 keV from the calculated mean proton energy in the target, 14.12 MeV, to assure that the correct region of the compound nucleus was reached by the inverse reaction. Data were taken in 10° steps between 25° and 155° and are summarized in Fig. 3.

For the ^{11}B ($\vec{p}$,d)^{10}B reaction, data were obtained at seven energies between $E_p = 11.34$ and 11.94 MeV in 100 keV steps over an angular range which varied with incident proton energy. At $E_p = 11.34$ MeV, the A_y angular distribution extends from 25° to 100° and increases 5° to 10° for each 100 keV increase in E_p (see Fig. 4). The target thickness in the polarization measurement was about 400 keV, therefore we measured A_y for a range of proton energies about $+200$ to -400 keV from the proton energy corresponding to the mean energy in the target for the inverse reaction, 11.76 MeV. These data are are presented in Fig. 4. Note the data shown in Fig. 4 are plotted in the laboratory reference frame.

In addition to the A_y angular distribution data, excitation functions were taken at two angles for both targets. The angles chosen were those for which the largest variations with energy had been observed in the A_y angular distributions. Also, for the ^{11}B target angles were chosen to avoid direct overlap of the deuteron peaks with proton groups. The ^{13}C target measurements were made every 33 keV between 13.79 and 14.42 MeV at laboratory scattering angles of 105° and 125°. For the ^{11}B target, data were obtained every 10 keV between 11.34 and 11.74 MeV at angles of 75° and 95° and were later extended at 95° in 20 keV steps to 12.0 MeV. These data are shown in Figs. 5 and 6. Since the excitation function step sizes are larger than the target thicknesses, the entire excitation regions have not been covered. The data in Figs. 5 and 6 reveal no evidence for narrow resonant structures greater in width than 13 and 4 keV, respectively.

III. POLARIZATION-ANALYZING POWER COMPARISON

We first compare P_y in ^{12}C(d,$\vec{p}$)^{13}C (Ref. 6) with A_y for ^{13}C($\vec{p}$,d)^{12}C measured in our work. Our

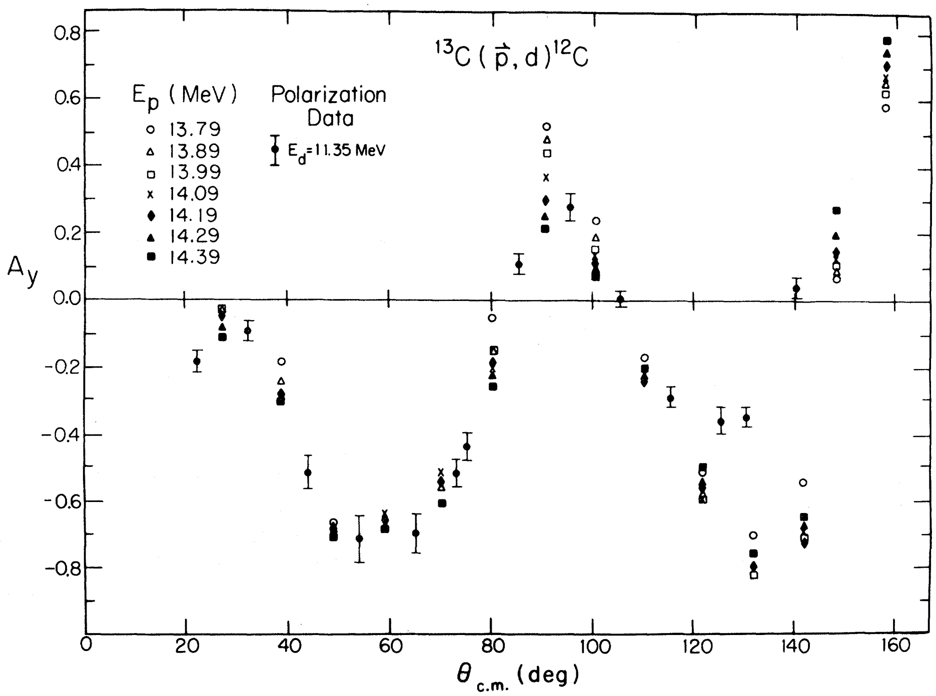

FIG. 3. Vector analyzing power distribution data at seven energies for the $^{13}C(\vec{p},d)^{12}C$ reaction are indicated by the geometric symbols. The uncertainty in each data point is less than or equal to the size of the symbol. Proton polarizations at 11.35 MeV for the $^{12}C(d,\vec{p})^{13}C$ reaction are indicated by solid dots with error bars.

values of A_y agree well with the P_y data for the angular range 20° to 100°; see Fig. 3. At angles beyond about 100°; the A_y and P_y data are in phase but differ substantially in amplitude. The cross section for the $^{12}C(d,\vec{p})^{13}C$ reaction drops by a factor of 10 from forward to back angles at $E_0 = 11.35$ MeV, according to Ref. 6. Already at $\theta = 25°$ the proton peak of interest in the spectrum exhibited in Ref. 6 has an appreciable background. Thus, in the angular region where experimental differences appear, the polarization measurement is less reliable

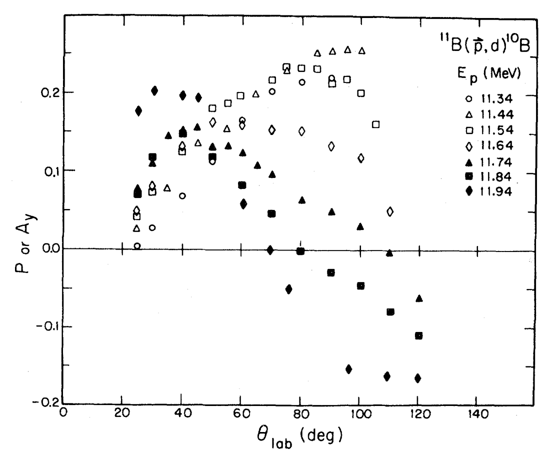

FIG. 4. Vector analyzing power distribution data at seven energies for the $^{11}B(\vec{p},d)^{10}B$ reaction are indicated by the geometric symbols. The uncertainty in each data point is less than or equal to the size of the symbol.

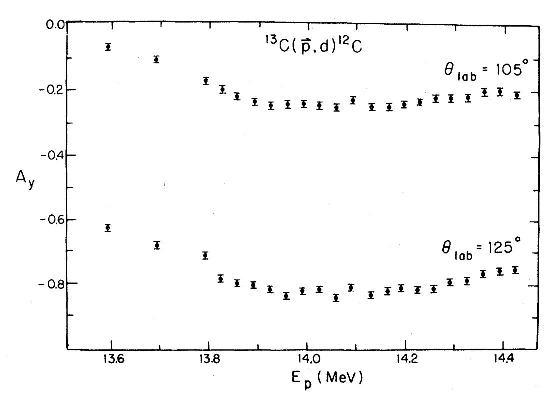

FIG. 5. Vector analyzing power excitation function data for the $^{13}C(\vec{p},d)^{12}C$ reaction at lab angles of 105° and 125°. The energy step size is 33 keV from 13.79 to 14.42 MeV.

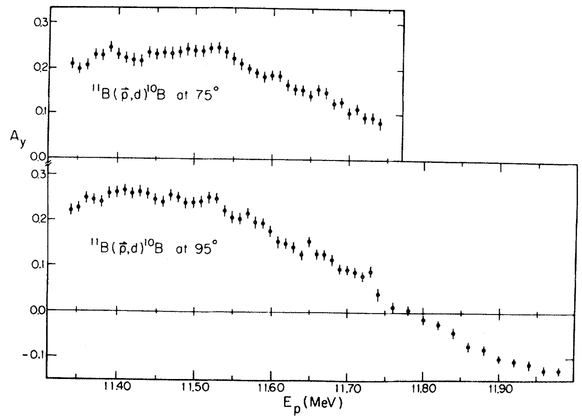

FIG. 6. Vector analyzing power excitation function data for the $^{11}B(\vec{p},d)^{10}B$ reaction at lab angles of 75° and 95°. The energy step size is 10 keV from 11.34 to 11.74 MeV and 20 keV for 11.74 to 12.0 MeV.

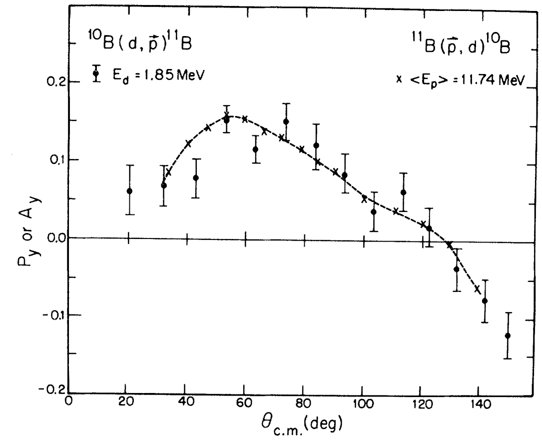

FIG. 7. Proton polarizations at 2.05 MeV for the $^{10}B(d,\vec{p})^{11}B$ reaction are indicated by solid dots with error bars. The × symbols are cross section-weighted average values of the vector analyzing power data of Fig. 4 for the $^{11}B(\vec{p},d)^{10}B$ reaction. The dashed line is a guide to the eye.

than both the A_y measurement of the inverse reaction and the forward angle polarization measurements. The discrepancies occur only over a small angular range where the polarization data are relatively difficult to obtain. This is unlike the results of Ref. 1, where substantial differences between P_y and A_y were seen at essentially all angles. The authors of Ref. 6 cannot now find any problem with their experiment which could explain these differences.[11] We contend that the observed difference between P_y and A_y in this comparison is not yet evidence for a violation of time-reversal invariance.

We next consider a comparison of P_y in $^{10}B(d,\vec{p})B^{11}$ (Ref. 7) and our A_y data for the inverse reaction. The proton bombarding energy of $E_p = 11.74$ MeV for the $^{11}B(\vec{p},d)^{10}B$ reaction was expected to match mean excitation energies in the compound nucleus, ^{12}C, with the time-reversed reaction for $E_d = 1.85$ MeV at the center of the ^{10}B target. The excitation function data of Fig. 6 imply a smooth decrease in A_y for this reaction over the 400 keV excitation energy region sampled by the deuteron beam in the thick target of the P_y measurement. Since the angular distributions of A_y in Fig. 4 indicate a regular energy dependence over this region, we have calculated an angular distribution of A_y for a mean proton energy of 11.74 MeV. This A_y distribution is the cross section-weighted average of the $^{11}B(\vec{p},d)^{10}B$ analyzing power data for $E_p = 11.54$ to 11.94 MeV. Note that at back angles, data was not available at each of the five energies. The cross sections used for this averaging process were interpolated from excitation function measurements in Ref. 12. The resulting mean A_y distribution is compared to the $^{10}B(d,\vec{p})^{11}B$ P_y data in Fig. 7. The dashed line of Fig. 7 is simply a guide to the eye through the cross section-weighted average of A_y data points. It is clear from this figure that current data present no evidence for a violation of the polarization-analyzing power equality in this pair of reactions. Agreement between the A_y and P_y data for this pair of reactions does not depend on the cross section data of Ref. 12. An A_y distribution calculated as the simple average of A_y data at the five energies, $E_p = 11.54$ to 11.94 MeV also falls within the error bars of the P_y distribution. The A_y data distribution for the mean energy, 11.74 MeV, equally well reproduces the P_y data.

IV. CONCLUSIONS

We have demonstrated good agreement between P_y for $^{12}C(d,\vec{p})^{13}C$ and $^{10}B(d,\vec{p})^{11}B$ with A_y for the time-reversed reactions, $^{13}C(\vec{p},d)^{12}C$ and $^{11}B(\vec{p},d)^{10}B$ at approximately matching excitation energies in the compound nuclei ^{14}N and ^{12}C, respectively. This agreement is consistent for both pairs of inverse reactions over a wide angular range; however, some differences between P_y and A_y persist at a limited number of backward angles in the carbon case. Certainly the differences observed between P_y and A_y in this work are not nearly as striking as in Ref. 1. Considering the experimental difficulties of measuring a statistically reliable polarization angular distribution, we see no convincing evidence in these data for the presence of a violation of the polarization-analyzing power equality in these single-nucleon transfer reactions.

ACKNOWLEDGMENTS

The authors are grateful to W. J. Thompson for many helpful discussions and wish to thank H. R. Weller for the use of his ^{13}C target. We also appreciate the cooperation of A. Budzanowski and G. Dietze. This research was supported in part by University of North Carolina Research Council grants and by the U. S. Department of Energy.

---

*Permanent address: Institut für Kernphysik der Universität Köln, D-5000 Köln 41, West Germany.

[1]H. E. Conzett *et al.*, *Polarization Phenomena in Nuclear Physics—1980,* Proceedings of the Fifth International Symposium on Polarization Phenomena in Nuclear Physics, Santa Fe, New Mexico, 1980, edited by G. G. Ohlsen, R. E. Brown, Nelson Jarmie, W. W. McNaughton, and G. M. Hale (AIP, New York, 1981), p. 1422; Recently published in Physical Review Letters see also R. J. Slobodrian, C. Rioux, R. Roy, H. E. Conzett, P. von Rossen, and F. Hinterburger, Phys. Rev. Lett. 47, 1803 (1981).

[2]C. S. Wu, E. Amble, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, Phys. Rev. 105, 1413 (1957).

[3]J. H. Christenson, J. W. Cronin, V. C. Fitch, and R. Turlay, Phys. Rev. Lett. 13, 138 (1964).

[4]D. E. Nagle *et al.*, *High Energy Physics with Polarized Beams and Polarized Targets (Argonne, 1978),* Proceedings of the Third International Symposium on High Energy Physics with Polarized Beams and Targets, edited by G. H. Thomas (AIP, New York, 1979).

[5]N. Lockyer *et al.*, Phys. Rev. Lett. 45, 1821 (1980).

[6]A. Budzanowski *et al.*, Nucl. Phys. A161, 610 (1971).

[7]G. Dietze and K. D. Stahl, Z. Phys. 228, 172 (1969).

[8]B. P. Hichwa and R. R. Cadmus, Jr., documentation for computer code MUFFIT, internal report of the University of Wisconsin Physics Department, Nuclear Physics Group, 1973 (unpublished).

[9]P. G. Ikossi *et al.*, Nucl. Phys. A225, 481 (1974).

[10]P. Schwandt, T. B. Clegg, and W. Haeberli, Nucl. Phys. A163, 432 (1971).

[11]A. Budzanowski, private communication.

[12]N. Arena *et al.*, Lett. Nuovo Cimento 5, 879 (1972).